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Specification and Drawings, as originally filed, with Application for Patent Serial No: CA 2274301, on June 10, 1999, by QUESTOR INDUSTRIES INC., assignee of Bowie G. Keefer, for "Chemical Reactor with Pressure Swing Adsorption".

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Agent certificateur/Certifying Officer

August 18, 2006

Date

(CIPO 68)  
31-03-04

Canada

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CHEMICAL REACTOR WITH PRESSURE SWING ADSORPTION

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ABSTRACT OF THE DISCLOSURE

A chemical reaction is performed with separation of the product(s) and reactant(s)e by  
10 pressure swing adsorption (PSA), using an apparatus having a plurality of adsorbers cooperating with first and second valve means in a PSA module, and with the PSA cycle characterized by multiple intermediate pressure levels between the higher and lower pressures of the PSA  
15 cycle. Gas flows enter or exit the PSA module at the intermediate pressure levels as well as the higher and lower pressure levels, entering from compressor stage(s) or exiting into exhauster or expander stages, under substantially steady conditions of flow and pressure.  
20 The PSA module comprises a rotor containing the adsorbers and rotating within a stator, with ported valve faces between the rotor and stator to control the timing of the flows entering or exiting the adsorbers in the rotor. The reaction may be performed within a  
25 portion of the rotor containing a catalyst.

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CHEMICAL REACTOR WITH PRESSURE SWING ADSORPTION

FIELD OF THE INVENTION

5       The invention relates to chemical reactions conducted in the gas or vapour phase. Reactions may be exothermic or endothermic, and may be conducted over a catalyst or under an appropriate form of external excitation to stimulate the reaction. Some particular 10 applications include ammonia synthesis, methanol synthesis, conversion of natural gas or syngas to liquid fuels, hydrogenation and dehydrogenation reactions, and controlled oxidation reactions.

15       BACKGROUND OF THE INVENTION

Fundamental problems in the chemical process industry include management of reaction equilibrium and kinetics to achieve high conversion with desired 20 selectivity under moderate reaction conditions, and management of the heat of reaction to control reaction temperature and to achieve high energy efficiency.

Typically, single pass conversion of the feed 25 reactant(s) is incomplete because of equilibrium limitations. It is then often necessary to provide a separation system to extract useful products from the reactor effluent, and then to recycle unconsumed reactants to the reactor inlet. The prior art provides 30 known separation processes based on condensation, distillation, membrane permeation, absorption, and adsorption. In most cases, these prior art separation processes are incompatible with the operating temperature of the reaction itself. Most conventional 35 separation processes operate at ambient or sub-ambient temperature, while the reaction operates at elevated

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temperature so that costly heat exchangers are required for the recycle loop.

High temperatures generally promote good reaction rates, but shift the equilibrium of exothermic reactions toward lower conversion. The high cost of heat exchangers, recycle compressors, and other auxiliary equipment then incentivizes operation at relatively severe pressure or temperature reaction conditions to minimize the need for recycle. In the typical exothermic reaction example of ammonia synthesis, satisfactory conversion is achieved by forcing the equilibrium with high pressure operation, while product separation from the recycle loop is achieved by condensation usually after refrigeration.

The present invention integrates the chemical reactor with pressure swing adsorption as the product/reactant separation process. Direct integration of PSA devices with chemical reaction has previously been disclosed by Keefer (U.S. Patent No. 4,702,903, U.S. Patent No. 4,816,121, and U.S. Patent No. 5,256,172), Kadlec et al (U.S. Patent No. 5,254,368), Dandekar et al (U.S. Patent No. 5,523,326) and Knaebel (U.S. Patent No. 5,711,926). Other sorption devices in chemical reaction processes have been disclosed by Lavie (U.S. Patent No. 4,537,760), Westerterp (U.S. Patent No. 4,731,387), Dandekar et al (U.S. Patent No. 5,449,696) and Lyon (U.S. Patent No. 5,827,496).

Gas separation by pressure swing adsorption (PSA) is achieved by coordinated pressure cycling and flow reversals over an adsorbent bed which preferentially adsorbs a more readily adsorbed component relative to a less readily adsorbed component of the mixture. The total pressure is elevated during

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intervals of flow in a first direction through the adsorbent bed from a first end to a second end of the bed, and is reduced during intervals of flow in the reverse direction. As the cycle is repeated, the less 5 readily adsorbed component is concentrated in the first direction, while the more readily adsorbed component is concentrated in the reverse direction.

A "light" product, depleted in the more 10 readily adsorbed component and enriched in the less readily adsorbed component, is then delivered from the second end of the bed. A "heavy" product enriched in the more strongly adsorbed component is exhausted from the first end of the bed. Typically, the feed is 15 admitted to the first end of a bed and the second product delivered from the second end of the bed when the pressure in that bed is elevated to a higher working pressure, while the second product is exhausted from the first end of the bed at a lower working pressure which 20 is the low pressure of the cycle.

The conventional process for gas separation by 25 pressure swing adsorption uses two or more adsorbent beds in parallel, with directional valving at each end of each adsorbent bed to connect the beds in alternating sequence to pressure sources and sinks, thus establishing the changes of working pressure and flow 30 direction. This conventional pressure swing adsorption process makes inefficient use of applied energy, because of irreversible expansion over the valves over large pressure differences while switching the adsorbent beds between higher and lower pressures.

Keefer (U.S. Pat. No. 5,256,172) discloses the 35 use of expansion turbines to recover power by the principle of thermally coupled pressure swing

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adsorption, in which expansion energy of the PSA cycle  
is recovered and heat may be applied directly through an  
integrated regenerative thermodynamic cycle  
(regenerative Brayton cycle, or a modified Ericsson  
5 cycle) as a supplemental energy source to perform  
pressure swing adsorption gas separations. A gas turbine  
heat recovery system for ammonia synthesis has been  
disclosed by Barber et al (U.S. Patent No. 4,224,299 and  
U.S. Patent No. 4,273,743).

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Siggelin (U.S. Patent No. 3,176,446), Mattia  
(U.S. Patent No. 4,452,612), Davidson and Lywood (U.S.  
Patent No. 4,758,253), Boudet et al (U.S. Patent No.  
5,133,784), and Petit et al (U.S. Patent No. 5,441,559)  
15 disclose PSA devices for ambient temperature operation,  
using rotary adsorbent bed configurations. Ports for  
multiple angularly separated adsorbent beds mounted on a  
rotor assembly sweep past fixed ports for feed  
admission, product delivery and pressure equalization;  
20 with the relative rotation of the ports providing the  
function of a rotary distributor valve. Related devices  
are disclosed by Kagimoto et al (U.S. Patent No.  
5,248,325) and LaCava et al (U.S. Patent No. 5,487,775).  
All of these prior art devices use multiple adsorbent  
25 beds operating sequentially on the same cycle, with  
multiport distributor rotary valves for controlling gas  
flows to, from and between the adsorbent beds.

30

Rotary PSA modules are used in copending U.S.  
Patent Application No. 08/995,906 to provide an  
inherently simple valving function for connecting a  
large number of cooperating adsorber elements  
sequentially to pressure sources and exhaust sinks at  
multiple narrowly spaced pressure intervals. Pressure  
35 and flow pulsations are preferably minimised by using a  
large number of equally angularly spaced adsorber

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elements in each module, while scale-up to the largest capacity ratings may be achieved by combining multiple rotary modules in parallel with a large compressor with a single prime mover.

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Important applications exist where the separation of carbon dioxide is desired at elevated temperature from a reactive gas mixture containing steam, or where such separation could greatly enhance process efficiency, simplicity and economics.

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#### DISCLOSURE OF INVENTION

The present invention conducts a chemical reaction in cooperation with a rotary module for pressure swing adsorption separation of the reaction product(s) from the reactant(s), with high energy efficiency and with compact machinery of low capital cost.

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The inventive apparatus includes a rotary module for PSA separation of a gas mixture containing a more readily adsorbed component and a less readily adsorbed component, with the more readily adsorbed component being preferentially adsorbed from the feed gas mixture by an adsorbent material under increase of pressure, so as to separate from the gas mixture a heavy product gas enriched in the more readily adsorbed component, and a light product gas enriched in the less readily adsorbed component and depleted in the more readily adsorbed component. The apparatus typically includes axial or centrifugal compression machinery cooperating with one or multiple PSA modules in parallel. Each PSA module comprises a plurality of adsorbers, with each adsorber having a flow path

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contacting adsorbent material between first and second ends of the flow path.

Each PSA module further has a first valve means cooperating with the adsorbers to admit feed gas to the first ends of the adsorbers, and to exhaust heavy product gas from the first ends of the adsorbers. Each PSA module also has a second valve means cooperating with the adsorbers to deliver light product gas from the second ends of the adsorbers, to withdraw light reflux gas from the second ends of the adsorbers, and to return light reflux gas to the second ends of the adsorbers. The term "light reflux" refers to withdrawal of light gas (enriched in the less readily adsorbed component) from the second ends of adsorbers via the second valve means, followed by pressure let-down and return of that light gas to other adsorbers at a lower pressure via the second valve means. The first and second valve means are operated so as to define the steps of a PSA cycle performed sequentially in each of the adsorbers, while controlling the timings of flow at specified total pressure levels between the adsorbers and the compression machinery.

The PSA process of the invention establishes the PSA cycle in each adsorber, within which the total working pressure in each adsorber is cycled between a higher pressure and a lower pressure of the PSA cycle. The PSA process also provides a plurality of intermediate pressures between the higher and lower pressure. The compression machinery of the apparatus in general include multistage axial or centrifugal compressors and expanders.

In the present invention, the feed compressor will typically supply feed gas, in several stages at

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discrete intermediate pressures for feed pressurization of the adsorbers as well as the higher pressure for light product production, to the first valve means. The exhauster will typically receive second product gas, in several stages at discrete intermediate pressures for countercurrent blowdown of the adsorbers as well as the lower pressure, from the first valve means. The light reflux expander may also perform pressure let-down on several separate light reflux stages, sequentially drawn from the second valve means at a set of discrete intermediate pressure levels, and after expansion returned to the second valve means at a lower set of discrete intermediate pressure levels. Heat exchangers may be provided to heat gas streams about to be expanded, for thermally boosted energy recovery.

In order for the flowing gas streams entering or exiting the compression machinery at each pressure level to be substantially uniform in pressure and velocity, each PSA module will preferably have a sufficiently large number of adsorbers for several adsorbers to be undergoing each step of the PSA cycle at any moment. During pressurization and blowdown steps, the several adsorbers passing through the step would be in sequentially phased converging approach to the nominal pressure level of each step by a throttling pressure equalization from the pressure level of the previous step experienced by the adsorbers. Flow is being provided to the adsorbers in a pressurization step or withdrawn in a blowdown step by the compression machinery at the nominal pressure level of that step. Hence flow and pressure pulsations seen by the compression machinery at each intermediate pressure level are minimal by averaging from the several adsorbers passing through the step, although each

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adsorber undergoes large cyclic changes of pressure and flow.

As set forth in copending U.S. Patent  
5 Application No. 08/995,906, a preferred way to provide a  
large number of adsorbers in a mechanically simple PSA  
module is to instal those adsorbers as angularly spaced  
elements in a rotor, whose opposed faces engaging across  
sealing faces with a ported stator sealing faces will  
10 provide the first and second valve means. By providing  
a sufficient number of ports with suitable angular  
spacing to accommodate each of the desired pressure  
levels (higher, lower and intermediate) in each of the  
first and second valve faces, a desired PSA cycle can be  
15 achieved.

If a smaller number of adsorbers is used in  
each PSA module, surge absorber chambers will be needed  
to isolate each stage of the compression machinery from  
20 excessive pulsations of flow and pressure. With  
sufficiently large surge absorber chambers, flow and  
pressure pulsations seen by the compression machinery  
are again minimized.

25 The principle of using compression and  
expansion machinery (with compression performed  
predominantly in communication with the first ends of  
the adsorbers, and expansion energy recovery performed  
on cocurrent blowdown from the second ends of the  
30 adsorbers) to generate a high performance PSA cycle is  
referred to as "Thermally Coupled Pressure Swing  
Adsorption" or TCPSA, because of the inherent heat  
pumping aspect resulting from a close mechanical analogy  
to Stirling or Ericsson cycle thermodynamic engines.

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Energy recovery is performed by expansion of countercurrent blowdown gas (when those steps are performed at superatmospheric pressure), and by expansion over the pressure letdown expanders between 5 the light reflux exit and return compartments. Heat exchangers may be optionally provided as compression intercoolers to reject heat of compression, and as heaters to heat either (or both) the countercurrent blowdown gas or the light reflux gas about to be 10 expanded. The heater may be provided with heat from an external source, or may use heat of compression from the compression intercoolers as another mode of energy recovery within the apparatus and process of the invention.

15

Adsorbers and the pressures in the first and second compartments. Pressure drops due to flow. The present invention provides multistage or split stream compression/expansion machinery for the multiple gas flows at multiple closely spaced intermediate pressure 20 levels, enabled by the present PSA process. The multistage machinery may be provided as separate machines operating in series or parallel, or preferably as multiple impellers in tandem on a single shaft within 25 a single casing.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a simplified schematic of a PSA 30 apparatus, and Fig. 2 shows a typical PSA cycle, in the format to which the invention shall be applied.

Fig. 3 shows a sectional view of a rotary module configured for radial flow.

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Fig. 4 shows a sectional view of a rotary module configured for axial flow.

5 Fig. 5 shows sectional views of the first valve face, the adsorbers, and the second valve face of the rotary module of Fig. 4.

10 Fig. 6 is a simplified schematic of an apparatus for conducting an exothermic reaction, with the chemical reaction performed within a zone of the adsorbers in the rotary module.

15 Fig. 7 is a simplified schematic of an apparatus for conducting an exothermic reaction, with the chemical reaction performed in reactors external to the rotary module.

20 Fig. 8 is a simplified schematic of an apparatus for conducting an endothermic reaction, with the chemical reaction performed in reactors external to the rotary module.

#### MODES FOR CARRYING OUT THE INVENTION

25 Figs. 1 and 2

Fig. 1 shows an elementary PSA apparatus 1 with an adsorber assembly 2 having a plurality of "N" cooperating adsorbers 3 in parallel. Each adsorber has a flow path 4 between first end 5 and second end 6 of the adsorber 3, with adsorbent material contacting the flow path. Cooperating with the adsorbers are first valve means 7 and second valve means 8. Arrow 9 indicates the direction of progression of the adsorbers 35 in being connected to ports of the first and second valve means as shown in Fig. 1. In the case of a

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rotary adsorber, as in the preferred embodiments of the invention, adsorber rotor 2 is shown in Fig. 1 unrolled in a 360° section about its rotary axis so that rotation causes the adsorbers to advance in the direction of arrow 9 to undergo the cycle of Fig. 2.

The left hand edge 13 of the unrolled view of rotor 2 returns to right hand edge 14 after rotation of 360°. It is also possible within the invention to have an integral multiple of "M" groups of "N" adsorbers in a single rotor 2, so that the angular extent for edge 13 to edge 14 is  $360^\circ/M$ . This has the disadvantage of greater complexity of fluid connections to the first and second valve means, but the advantages of slower rotational speed (by a factor of "M" for the same PSA cycle frequency) and a symmetric pressure and stress distribution. With "M" = 2, Fig. 1 represents each 360° side of a rotor according to the invention.

Fig. 2 shows the PSA cycle undergone sequentially by each of the "N" adsorbers 3 over a cycle period "T". The cycle in consecutive adsorbers is displaced in phase by a time interval of  $T/N$ . In Fig. 2 the vertical axis 10 indicates the working pressure in the w within the adsorber elements are here neglected. The higher and lower working pressures of the PSA process are respectively indicated by dotted lines 11 and 12.

The horizontal axis 15 indicates time, with the PSA cycle period defined by the time interval between points 16 and 17. At times 16 and 17, the working pressure in adsorber 3 is pressure 18. Starting from time 16, the cycle begins as the first end 5 of adsorber 3 is opened by the first valve means 7 to first feed supply means 20 at the first intermediate feed

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pressure 21. The pressure in that adsorber rises from pressure 18 at time 17 to the first intermediate feed pressure 21. Proceeding ahead, the first end 5 is opened next to second feed supply means 22 at the second 5 intermediate feed pressure 23. The adsorber pressure rises to the second intermediate feed pressure.

Then the first end 5 is opened to a third feed supply means 24 at the higher pressure of the PSA process. Once the adsorber pressure has risen to substantially the higher working pressure, its second 10 end 6 is opened by the second valve means to light product delivery conduit 25 to deliver purified light product. While feed gas is still being supplied to the first end of adsorber 3 from the third feed supply means, the second end 6 is next closed to light product delivery conduit 25, and is opened to deliver "light reflux" gas (enriched in the less readily adsorbed component, similar to second product gas) by conduit 29 15 to first light reflux pressure let-down means 30. The light reflux pressure let-down means may be an expander with optional heat exchangers such as an inlet heater, or a throttle orifice. All or some of the feed supply 20 means may be feed compression stages.

25 The first end 5 of adsorber 3 is then closed by the first valve means, while the second end 6 is opened successively by the second valve means to (a) drop the adsorber pressure to the first cocurrent 30 blowdown pressure 32 while delivering light reflux gas by conduit 33 to second light reflux pressure letdown means 34, (b) drop the adsorber pressure to the second cocurrent blowdown pressure 36 while delivering light reflux gas by conduit 37 to third light reflux pressure 35 letdown means 38, and (c) drop the adsorber pressure to the third cocurrent blowdown pressure 40 while

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delivering light reflux gas by conduit 41 to fourth  
light reflux pressure letdown means 42. Second end 6 is  
then closed for an interval, until the light reflux  
return steps following the countercurrent blowdown  
5 steps.

The light reflux pressure let-down means may  
be mechanical expansion stages for expansion energy  
recovery, or may be restrictor orifices or throttle  
10 valves for irreversible pressure let-down.

Either when the second end 6 is closed after  
the final light reflux exit step (as shown in Fig. 2),  
or earlier while light reflux exit steps are still  
15 underway, first end 5 is opened to first exhaust means  
46, dropping the adsorber pressure to the first  
countercurrent blowdown intermediate pressure 48 while  
releasing "heavy" gas (enriched in the more strongly  
adsorbed component) to the first exhaust means. Next,  
20 first end 5 is opened to second exhaust means 50,  
dropping the adsorber pressure to the second  
countercurrent blowdown intermediate pressure 52 while  
releasing "heavy" gas. Then first end 5 is opened to  
third exhaust means 54, dropping the adsorber pressure  
25 to the lower pressure 12 of the PSA process while  
releasing "heavy" gas. Once the adsorber pressure has  
substantially reached the lower pressure while first end  
5 is open to the third exhaust means 54, the second end  
6 is opened to receive fourth light reflux gas (as purge  
30 gas) from fourth light reflux pressure let-down means 42  
by conduit 55 in order to displace more heavy gas into  
the third exhaust means. The heavy gas from the first,  
second and third exhaust means may be delivered together  
as the heavy product 56. All or some of the exhaust  
35 means may be mechanical exhauster stages, alternatively  
either expansion stages if the pressure is to be

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reduced, or vacuum pumping stages if the pressure is to be increased to ambient pressure, or exhaust compression stages if the exhaust of second product is to be delivered at an elevated pressure. An exhaust means may 5 also be provided by venting to an external sink, e.g. the ambient atmosphere.

The adsorber is then repressurized by light reflux gas after the first end 5 is closed. In 10 succession, the second end 6 is opened (a) to receive light reflux gas by conduit 59 from the third light reflux pressure letdown means 38 to raise the adsorber pressure to the first light reflux pressurization pressure 60, (b) to receive light reflux gas by conduit 61 from the second light reflux pressure letdown means 34 to raise the adsorber pressure to the second light reflux pressurization pressure 62, and (c) to receive light reflux gas by conduit 63 from the first light reflux pressure letdown means 30 to raise the adsorber 15 pressure to the third light reflux pressurization pressure. Unless feed pressurization has already been started while light reflux return for light reflux 20 pressurization is still underway, the process begins feed pressurization for the next cycle after time 17 as 25 soon as the third light reflux pressurization step has been concluded.

From each feed supply means (e.g. 20), the feed flow is delivered by a conduit 70 through an 30 optional surge absorber chamber 71 to a feed compartment 72 opening to a feed port 73 in first valve means 7. Feed compartment 72 may be open to several adsorbers simultaneously, and may have a restricted entrance 74 so as to provide a gradual throttling equalization of 35 pressure as each adsorber is opened to feed compartment 72. First feed pressurization compartment 72 is fed

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by conduit 70, second feed pressurization compartment 75 is fed by conduit 76, and feed production supply compartment 77 is fed by conduit 78.

5           To each exhaust means (e.g. 46), the exhaust flow is delivered by a conduit 80 through an optional surge absorber chamber 81 from an exhaust compartment 82 opening to an exhaust port 83 in first valve means 7. Exhaust compartment 82 may be open to several adsorbers 10 simultaneously, and may have a restricted entrance 84 so as to provide a gradual throttling equalization of pressure as each adsorber is opened to exhaust compartment 82. To label the exhaust compartments, first countercurrent blowdown exhaust compartment 82 15 exhausts to conduit 80, a second countercurrent blowdown exhaust compartment 61 exhausts to conduit 63, and a purge exhaust compartment 65 exhausts to conduit 67.

20           To light product delivery conduit 25, the light product is delivered through an optional surge absorber chamber 86 from light product exit compartment 87 opening to a light product port 88 in second valve means 8.

25           To each light reflux pressure letdown means (e.g. 34), the light reflux flow is delivered by a conduit 90 through an optional surge absorber chamber 91 from a light reflux exit compartment 92 opening to a light reflux exit port 93 in second valve means 8. Light reflux exit compartment 92 may be open to several adsorbers 30 simultaneously, and may have a restricted entrance 94 so as to provide a gradual throttling equalization of pressure as each adsorber is opened to light reflux exit compartment 92.

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From each light reflux pressure letdown means (e.g. 34), the light reflux flow is delivered by a conduit 95 through an optional surge absorber chamber 96 to a light reflux entrance compartment 97 opening to a light reflux entrance port 98 in second valve means 8. Light reflux exit compartment 97 may be open to several adsorbers simultaneously, and may have a restricted entrance 99 so as to provide a gradual throttling equalization of pressure as each adsorber is opened to light reflux entrance compartment 97.

The rate of pressure change in each pressurization or blowdown step may thus be restricted by throttling in compartments of the first and second valve means, or by throttling in the ports at first and second ends of the adsorbers, resulting in the typical pressure waveform depicted in Fig. 2. Excessively rapid rates of pressure change would subject the adsorber to mechanical stress, while also causing flow transients which would tend to increase axial dispersion of the concentration waveform in the adsorber. Pulsations of flow and pressure are minimized by having a plurality of adsorbers simultaneously transiting each step of the cycle, and/or by providing surge absorbers in the conduits connecting to the first and second valve means.

It will be evident that the cycle shown in Fig. 2 could be generalized by having more or fewer intermediate stages in each major step of feed pressurization, countercurrent blowdown exhaust, or light reflux. Furthermore, in air separation or air purification applications, a stage of feed pressurization (typically the first stage) could be performed by equalization with atmosphere as an intermediate pressure of the cycle. Similarly, a stage of countercurrent blowdown could be performed by

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equalization with atmosphere as an intermediate pressure of the cycle.

Fig. 3

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Fig. 3 shows a sectional view of a rotary module configured for radial flow. Rotor 2 contains the "N" adsorbers 3, with the flow path here oriented radially between first end 5 and second end 6 of the adsorbers. The adsorber first ends 5 open by apertures 106 to a sealing face 107 with the first valve stator 108, which has ports 109 to define the first valve means 7. First valve stator 108 has a plurality of functional compartments in fluid communication to sealing face 107 by ports 109, including a first feed pressurization supply compartment 72, a second first feed pressurization supply compartment 75, a feed production supply compartment 77 at substantially the higher pressure, a first countercurrent blowdown exhaust compartment 82, a second countercurrent blowdown exhaust compartment 61, and a purge exhaust compartment 65 at substantially the lower pressure.

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The adsorber second ends 6 open by apertures 118 to a sealing face 119 with the second valve stator 105 which has ports 120 to define the second valve means 8. Second valve stator 105 includes, with each compartment in fluid communication to sealing face 119 by ports 120, a light product delivery compartment 87 at substantially the higher pressure, a first light reflux exit compartment which is here simply the downstream end of compartment 87 delivering gas to conduit 25, a second light reflux exit compartment 92 delivering gas to conduit 33, third and fourth light reflux exit compartments delivering gas to conduits 37 and 41 respectively, a fourth light reflux return compartment

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97 receiving purge gas from conduit 55 at substantially the lower pressure, a third light reflux return compartment receiving gas from conduit 59, a second light reflux return compartment receiving gas from conduit 61, and a first light reflux return compartment receiving gas from conduit 63. The angular spacing of ports communicating to the compartments in the first and second valve stators defines the timing of the PSA cycle steps similar to the cycle of Fig. 2.

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In this example, sealing faces 107 and 119 are respectively defined by the outer and inner radii of the annular rotor 2. Fluid sealing between the functional compartments in sealing face is achieved by clearance seals. The clearance seals are provided as slippers 130 attached to the first and second valve stators by partitions 131. Partitions 131 provide static sealing between adjacent compartments. Slippers 130 engage the sealing faces with narrow fluid sealing clearances, which also provide throttling of gas flows between the adsorbers and functional compartments in each pressure-changing step, so that each adsorber may smoothly equalize in pressure to the pressure of the next functional compartment about to be opened to that adsorber. In addition to the functional compartments, static pressure balancing compartments (e.g. 132 and 133) are provided behind some clearance seal slippers. The static pressure balancing compartments are disposed in angular sectors of the first and second valve stators not used as functional compartments, in order to establish a controlled pressure distribution behind the clearance slippers so as to maintain their positive sealing engagement without excessive contact pressure and consequent friction.

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Figs. 4 and 5

Fig. 4 shows a sectional view of a rotary module 200 configured for axial flow, while Fig. 5 shows 5 sectional views of the first valve face, the adsorbers, and the second valve face of the rotary module of Fig. 4. The flow path in adsorbers 3 is now parallel to axis 201. The steps of the process and functional compartments are still in the same angular relationship 10 regardless of a radial or axial flow direction in the adsorbers. Sections 200A, 200B and 200C are cross sections of module 200 in the planes respectively defined by arrows 202 - 203, 204 - 205, and 206 - 207. Fig. 4 is an axial section of module 200 through 15 compartments 77 and 87 at the higher pressure, and compartments 65 and 97 at the lower pressure. The adsorber rotor 2 contains the "N" adsorbers 3 in adsorber wheel 208, and revolves within stator 103. At the ends of rotor 2, circumferential seals 215 and 20 216 bound first sealing face 107, and circumferential seals 217 and 218 bound second sealing face 119. The sealing faces are flat discs. The circumferential seals also define the ends of clearance slippers 130 in the sealing faces between the functional compartments. 25 Rotor 2 is supported by bearing 220 in housing 225, which is integrally assembled with the first and second valve stators. Rotor 2 is driven by rim drive motor 230, which may have a friction, geared or belt engagement with the outer rim of rotor 2.

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Section 200A is shows the first valve face of embodiment 200 of Fig. 3, at section 202 - 203, with fluid connections to feed and to countercurrent blowdown. Arrow 270 indicates the direction of 35 rotation by adsorber rotor 2. The open area of valve face 107 ported to the feed and exhaust compartments is

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indicated by clear angular segments 77, 82, 61, 65, 72, 5  
75, and 77 corresponding to those functional compartments, between circumferential seals 215 and 216. The substantially closed area of valve face 107 between functional compartments is indicated by cross-hatched sectors 275 and 276 which are clearance slippers 130. Typical closed sector 275 provides a transition for an adsorber, between being open between two adjacent compartments. Gradual opening is provided by a tapering 10 clearance channel between the slipper and the sealing face, so as to achieve gentle pressure equalization of an adsorber being opened to a new compartment. Much wider closed sectors (e.g. 276) are provided to substantially close flow to or from one end of the 15 adsorbers when pressurization or blowdown is being performed from the other end.

Section 200 C is the second valve face of embodiment 200 of Fig. 3, at section 204 - 205. Similar principles and alternatives apply to radial flow and axial flow geometries, respectively sealing on cylindrical or disc faces. 20

Section 200 B is an adsorber wheel configuration for the embodiment of Fig. 3, at section 206 - 207. The adsorber configuration is similar to a radial flow geometry shown in copending U.S. Patent Application No. 08/995,906. Here, "N" = 72. The adsorbers 3 are mounted between outer wall 280 and inner wall 281 of adsorber wheel 208. Each adsorber comprises a rectangular flat pack which is laminated of adsorbent sheets 282, with spacers between the sheets to define flow channels here in the axial direction. Separators 284 are provided between the adsorbers to fill void space and prevent leakage between the adsorbers. 25 30 35

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The adsorbent sheets comprise a reinforcement material, in preferred embodiments glass fibre, metal foil or wire mesh, to which the adsorbent material is attached with a suitable binder. Typical adsorbents 5 include zeolites, many of which are also active as catalysts for reactions of interest. The zeolite crystals are bound with silica, clay and other binders, or self-bound, within the adsorbent sheet matrix.

Satisfactory adsorbent sheets have been made by coating a slurry of zeolite crystals with binder constituents onto the reinforcement material, with successful examples including nonwoven fiber glass scrims, woven metal fabrics, and expanded aluminum 15 foils. Spacers are provided by printing or embossing the adsorbent sheet with a raised pattern, or by placing a fabricated spacer between adjacent pairs of adsorbent sheets. Alternative satisfactory spacers have been provided as woven metal screens, non-woven fiber glass 20 scrims, and metal foils with etched flow channels in a photolithographic pattern.

Typical experimental sheet thicknesses have 25 been 150 microns, with spacer heights in the range of 100 microns, and adsorber flow channel length approximately 20 cm.

Fig. 6

An apparatus 300 for conducting an exothermic reaction, in the example of ammonia synthesis, conducts the reaction within a zone 301 adjacent the second ends 30 6 of the adsorbers 3 in the rotary module. Zone 301 has catalyst active for stimulating the reaction in an extended portion of the adsorbers, with the catalyst 35 preferably supported on sheets in a laminated parallel

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passage structure as described above for adsorbent sheets. The flow paths through the rotor include flow channels contacting adsorbent material, and the catalyst in a zone 301 thereof.

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The lower part of Figs. 6, 7 and 8 shows the PSA cycle pressure pattern, coordinated on horizontal time axis 305 with the angular sequence of the functional compartments in the first and second valve faces 7 and 8 as shown in the upper part of Figs. 6, 7 and 8. The vertical pressure axis 306 spans the PSA cycle lower pressure 307, upper pressure 308, and an intermediate pressure 309.

15

The first end 5 of the adsorbers 3 are maintained at approximately a first temperature T1 by heat exchanger means 310 cooperating with the conduits communicating with the second function compartments. The second end 6 of the adsorbers 3 are maintained at approximately a second temperature T2 by heat exchanger means 311 cooperating with the conduits communicating with the second function compartments. The reaction is conducted at elevated temperature, approximately temperature T1. A product of the reaction is condensed in a product separator 320 at a lower temperature, which may be approximately temperature T2.

20

With a large temperature difference between T1 and T2, the adsorbers must support a corresponding temperature gradient along the flow path, and consequently cyclic regenerative heat exchange will take place between the cyclically reversing gas flow in the flow path and the heat capacity of solid material in the flow path including the adsorbent material, any adsorbent support material and reinforcement thereof, and any spacers associated with flow channels. It is

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therefore preferred to incorporate ample solid material  
heat capacity in the flow path, and with intimate  
thermal contact to the flow channels. Desirably, the  
thermal conduction path in the solid material along the  
5 flow path is interrupted at frequent intervals, so as  
to avoid a large thermal conductance of the solid material  
along the flow path. It is also desirable to layer the  
adsorbent material with optimally selected adsorbents in  
different zones (e.g. adsorbent zones 328 and 329  
10 divided by zone boundary 330) of differing temperature.  
Apparatus 300 includes a multistage compressor 340 with  
multiple inlet and delivery ports for receiving gas  
enriched in the more adsorbed component from conduits  
80, 63 and 67, and compressing that gas back to conduits  
15 80, 63 and 67. The process thus includes withdrawing gas  
enriched in the more readily adsorbed component from the  
first valve face, compressing that gas to an increased  
pressure, and refluxing that gas to the first valve face  
and thence the flow paths at the increased pressure, so  
20 as to increase the concentration of the more readily  
adsorbed component adjacent the first valve face.  
Following a stage 341 of compressor 340, a stream gas  
enriched in the more readily adsorbed component is  
25 passed through condenser 320 from which a liquid product  
of reaction is delivered in conduit 342, a purge stream  
is optionally delivered by conduit 343 to remove any  
accumulating inert components, and an overhead stream is  
returned by conduit 344 to the inlet of the next stage  
30 of compressor 340 and thence to the first valve face, or  
else directly to the first valve face.

The apparatus also includes a multistage  
expander for receiving gas relatively enriched in the  
less readily adsorbed component from conduits 25, 33, 37  
35 and 41 communicating to the second valve face, and  
expanding that gas in parallel streams for return to the

- 24 -

second valve face by conduits 61, 59, 55 and 63 respectively.

5           The apparatus includes a feed supply conduit 359 and an optional feed compressor 360 for supplying a feed gas of the reactants(s) to one or more gas streams entering the first valve face.

10          Compressor 340 is a heavy reflux compressor and expander 350 is a light reflux expander for performing the PSA cycle. Heavy reflux compressor 340 and feed compressor 360 may be coupled on a single shaft 361 to light reflux expander 350 and a prime mover 362. 15          If the power output of expander 350 exceeds power consumption of compressors 341 and 360, prime mover 362 may be replaced with a generator or other mechanical load to absorb power usefully.

20          In the example of ammonia synthesis, the reactants are hydrogen and nitrogen which react to produce ammonia, typically over a promoted iron catalyst at a temperature T2 in the approximate range of 400° C to 500° C. A bench scale apparatus, using a compression piston to provide the function of the heavy reflux compressor and using an expansion piston to provide the function of the light reflux compressor, was operated with a single granular adsorber in the mechanical embodiment of U.S. Patent No. 4,702,903. The adsorber 25         was loaded with reduced iron catalyst 301, 13-X zeolite as the adsorbent in zone 309, and silica gel as the adsorbent in zone 308 according to the reference numerals of the present invention. The upper pressure 30         of the PSA cycle was approximately 800 kPa, and the lower pressure was approximately 400 kPa. The feed was 35         a mixture of hydrogen and nitrogen. Gas composition

- 25 -

adjacent the second end 6 was approximately 70% hydrogen, 28% nitrogen, and 2 % ammonia. Composition of product (delivered as vapour) from adjacent the second end was approximately 0% hydrogen, 40% nitrogen  
5 and 60% ammonia. Hence the directly integrated reactor and PSA device was able to produce and concentrate ammonia product, achieving 100 % conversion of feed hydrogen, while shifting the reaction equilibrium so as present a low concentration of the product component  
10 over the catalyst so as to enhance the reaction rate of this exothermic reaction at remarkably low pressure.

The apparatus of the present invention enables practicable scale-up and economic realization of a  
15 process similar to that of U.S. Patent No. 4,702,903, using rotational rather than reciprocating machinery.

Fig. 7

20 Embodiment 400 is another apparatus for conducting an exothermic reaction, similar to embodiment 300 but with the chemical reaction performed in reactors external to the rotary module. This apparatus may also be applied to ammonia synthesis.  
25

Reactors 401, 402, 403 and 404 contain an appropriate catalyst, and are interposed respectively in conduits 25, 33, 37 and 41 to receive gas enriched in the less readily adsorbed reactant components. It will  
30 be noted that the reactors operate at different pressures which are steady for each reactor. Optionally, reactors 402, 403 and 404 could be deleted.

35 The exothermic heat of reaction is taken up as heat of expansion in the light reflux expander 350, so as to maintain the desired reaction temperature T2,

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while also recovering that heat as work of mechanical expansion.

Fig. 8

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Embodiment 500 is an apparatus for conducting an endothermic reaction, with the chemical reaction performed in reactors external to the rotary module. An example application is ammonia dissociation to generate  
10 reducing gas as hydrogen.

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Reactors 501, 502 and 503 are interposed in conduits 78, 76 and 70 supplying gas to the first valve face 7. If desired, only one reactor could be provided. A feed gas containing a relatively more readily adsorbed reactant is supplied to a stage of heavy reflux compressor 340 by infeed conduit 504, which may as needed include a vaporizer 505 to ensure that the reactant(s) are in the vapour phase. Gas enriched in a more readily adsorbed reactant component is withdrawn as heavy reflux gas by conduits 80, 63 and 67 from countercurrent blowdown and exhaust compartments in the first valve face, and is thence delivered to inlet ports of heavy reflux compressor stages. The heavy reflux gas is compressed and is thereby heated by the heat of compression. Optionally, the compressed heavy reflux gas may be further heated from an external source of higher temperature heat in heat exchanger 510, before admission to reactors 501, 502 and 503. In this embodiment, T<sub>2</sub> is typically greater than T<sub>1</sub>, while the temperature of the compressed heavy reflux gas stream entering the reactors (after heavy reflux compression and heating, and any further heating by a heat exchanger 510) will be much greater than T<sub>2</sub> (the exit temperature of the exothermic reactors) so that the endothermic heat of reaction may be carried into the reactors as sensible

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heat of the reactor feed. Alternatively or additionally, the endothermic reactors may be heated externally by a furnace or by other means known in the art.

5

A purified stream of gas enriched in the less readily adsorbed product components is delivered at approximately the upper pressure by product delivery conduit 520. This stream would be hydrogen and nitrogen, completely purified of ammonia, in the example of ammonia dissociation. In that example, the present invention provides the important advances of 100% conversion of the feed, delivery of a purified product, and practicable operation of the catalytic reactor at much reduced temperature compared to the prior art, because the reactant is concentrated over the catalyst.

While only preferred embodiments of the invention have been described herein in detail, the invention is not limited thereby and modifications can be made within the scope of the attached claims.

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THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A process for conducting a chemical reaction which has a gas phase reactant and a gas phase product, while performing separation by pressure swing adsorption of the product component from the reactant component over an adsorbent material on which one of the reactant and the product components is a more readily adsorbed component and the other is a less readily adsorbed component under increase of pressure, the process including the steps of:
  - (a) introducing a feed gas containing the reactant component to a reaction space,
  - (b) conducting the reaction within the reaction space so as to obtain a gas mixture containing the reactant and the product components
  - (c) contacting the gas mixture containing the reactant and the product components with the adsorbent material in flow paths extending between first and second valve faces in a rotor,
  - (d) supplying gas to the first or second valve face at incrementally increasing pressures to an upper pressure of the process,
  - (e) withdrawing gas from the first or second valve face at incrementally decreasing pressures to a lower pressure of the process, and
  - (f) rotating the rotor at a rotational speed so as to establish cyclic fluid communication for each of the flow paths through the first and second valve faces in a cyclic sequence, so as to establish flow in each flow path directed from the first valve face to the second valve face at substantially the upper pressure, and to establish flow in each flow path directed

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from the second valve face to the first valve face at substantially the upper pressure.

2. The process of claim 1, in which the reactant  
5 component is the less readily adsorbed component, and withdrawing a product enriched in the more readily adsorbed component from adjacent the first valve face.
- 10 3. The process of claim 2, further withdrawing gas enriched in the more readily adsorbed component from the first valve face, compressing that gas to an increased pressure, and refluxing that gas to the first valve face and thence the flow paths at the  
15 increased pressure, so as to increase the concentration of the more readily adsorbed component adjacent the first valve face.
4. The process of claim 2, in which the reaction is  
20 exothermic.
5. The process of claim 4, in which a first reactant component is hydrogen, a second reactant component is nitrogen, and the product component is ammonia.  
25
6. The process of claim 4, in which a first reactant component is hydrogen, a second reactant component is carbon monoxide, and the product component is methanol.  
30
7. The process of claim 4, in which a first reactant component is hydrogen, a second reactant component is carbon monoxide, and the product component is a hydrocarbon which is liquid at ambient temperature.

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8. The process of claim 4, in which a first reactant component is methane, a second reactant component is oxygen, and the product component is a higher hydrocarbon.  
5
9. The process of claim 8, in which a first reactant component is methane, a second reactant component is oxygen, and the product component is ethylene.
10. The process of claim 1, in which the reactant component is the more readily adsorbed component, and withdrawing a product enriched in the less readily adsorbed component from adjacent the second valve face.  
15
11. The process of claim 10, further withdrawing gas enriched in the less readily adsorbed component from the second valve face, expanding that gas to a reduced pressure not less than the lower pressure, and refluxing that gas to the second valve face and thence the flow paths at the reduced pressure, so as to increase the concentration of the less readily adsorbed component adjacent the second valve face.  
20
12. The process of claim 2, in which the reaction is endothermic.  
25
13. The process of claim 8, in which the reactant component is ammonia, a first product component is hydrogen, and a second component is nitrogen.  
30
14. The process of claim 8, in which the reactant component is methanol, a first product component is hydrogen, and a second component is carbon monoxide.  
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15. The process of claim 8, in which a first reactant component is methanol, a second reactant component is water vapour, a first product component is hydrogen, and a second component is carbon dioxide.  
5
16. The process of claim 1, further maintaining the temperature of the flow path adjacent the first valve face approximately at a first temperature, and maintaining the temperature of the flow path adjacent the second valve face approximately at a second temperature.  
10
17. The process of claim 1, maintaining the first temperature to be greater than the second temperature, and exchanging heat between the gas mixture in the flow paths and solid material with heat capacity disposed along the flow paths.  
15
18. The process of claim 1, maintaining the second temperature to be greater than the first temperature, and exchanging heat between the gas mixture in the flow paths and solid material with heat capacity disposed along the flow paths.  
20
19. The process of claim 1, further conducting the reaction within the flow paths, a portion of each of which being a reaction space.  
25
20. Apparatus for conducting a chemical reaction which has a gas phase reactant component and a gas phase product component, one of the reactant and the product components being a more readily adsorbed component and the other being a less readily adsorbed component under pressure increase over an adsorbent material, the apparatus comprising:  
30  
35

- (a) a rotary module for pressure swing adsorption separation of a gas mixture containing the reactant and product components, the rotary module comprising a stator and a rotor with an axis of rotation, the stator and rotor being mutually engaged in fluid communication across a first rotary valve surface and a second rotary valve surface both centred on the axis of rotation; the stator having a plurality of first function compartments each opening into the first rotary valve surface in an angular sector thereof, and a plurality of second function compartments each opening into the second rotary valve surface in an angular sector thereof; the rotor having a plurality of angularly spaced adsorber elements wherein the adsorbent material contacts flow paths extending in a flow direction between a first end communicating by a first aperture to the first valve surface and a second end communicating by a second aperture to the second valve surface, and with means to rotate the rotor such that each of the first apertures is opened in fluid communication to the first function compartments by rotation of the rotor bringing the apertures sequentially into the angular sector of each first function compartment, while each of the second apertures is opened in fluid communication to the second function compartments by rotation of the rotor bringing the apertures sequentially into the angular sector of each second function compartment so as to achieve cycling of the pressure in each adsorber element between an upper pressure and a lower pressure,



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24. The apparatus of claim 23, in which the means to stimulate the chemical reaction is a heterogeneous catalyst.
- 5      25. The apparatus of claim 20, in which the reaction is exothermic, and the reactant component is a less readily adsorbed component while the product component is a more readily adsorbed component.
- 10     26. The apparatus of claim 25, with compressor means for withdrawing gas enriched in the more readily adsorbed component from the first valve face, compressing that gas to an increased pressure, and refluxing that gas to the first valve face and thence the flow paths at the increased pressure, so as to increase the concentration of the more readily adsorbed component adjacent the first valve face.
- 15     27. The apparatus of claim 20, in which the reaction is endothermic, and the reactant component is a more readily adsorbed component while the product component is a less readily adsorbed component.
- 20     28. The apparatus of claim 27, with pressure let-down means for withdrawing gas enriched in the less readily adsorbed component from the second valve face, expanding that gas to a reduced pressure not less than the lower pressure, and refluxing that gas to the second valve face and thence the flow paths at the reduced pressure, so as to increase the concentration of the more readily adsorbed component adjacent the second valve face.
- 25     29. Rotary module for conducting a chemical reaction which has a gas phase reactant component and a gas phase product component and for separating the
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product component from the reactant component by pressure swing adsorption, one of the reactant and the product components being a more readily adsorbed component and the other being a less readily adsorbed component under pressure increase over an adsorbent material, the rotary module comprising a stator and a rotor with an axis of rotation, the stator and rotor being mutually engaged in fluid communication across a first rotary valve surface and a second rotary valve surface both centred on the axis of rotation; the stator having a plurality of first function compartments each opening into the first rotary valve surface in an angular sector thereof, and a plurality of second function compartments each opening into the second rotary valve surface in an angular sector thereof; the rotor having a plurality of angularly spaced flow paths each extending in a flow direction between a first end communicating by a first aperture to the first valve surface and a second end communicating by a second aperture to the second valve surface, with the adsorbent material contacting a flow channel within each flow path and with a reaction space for conducting the chemical reaction within each flow path; with means to rotate the rotor such that each of the first apertures is opened in fluid communication to the first function compartments by rotation of the rotor bringing the apertures sequentially into the angular sector of each first function compartment, while each of the second apertures is opened in fluid communication to the second function compartments by rotation of the rotor bringing the apertures sequentially into the angular sector of each second function compartment so as to achieve cycling of the pressure in each adsorber element between an upper pressure and a

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lower pressure established by compression and expansion means cooperating with the function compartments.

- 5        30. The rotary module of claim 29, wherein the function compartments also include a plurality of pressurization compartments for subjecting the flow paths to a plurality of incremental pressure increases between the upper and lower pressures.
- 10      31. The rotary module of claim 30, wherein the pressurization compartments include feed pressurization compartments opening into the first rotary valve surface for delivering the gas mixture to the flow paths at incrementally different pressures intermediate between the upper and lower pressures.
- 15      32. The rotary module of claim 30, wherein the pressurization compartments include light reflux return compartments opening into the second rotary valve surface for delivering gas enriched in a less readily adsorbed component to the flow paths at a plurality of incrementally different pressures.
- 20      33. The rotary module of claim 29, wherein the function compartments also include a plurality of blowdown compartments for subjecting the flow paths to a plurality of incremental pressure decreases between the upper and lower pressures.
- 25      34. The rotary module of claim 33, wherein the blowdown compartments include light reflux exit compartments opening into the second stator valve surface for removing gas enriched in a less readily adsorbed
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component as cocurrent blowdown from the flow paths at a plurality of incrementally different pressures.

- 5        35. The rotary module of claim 33, wherein the blowdown compartments include countercurrent blowdown compartments opening into the first stator valve surface for removing gas enriched in a more readily adsorbed component from the flow paths at a plurality of incrementally different pressures.
- 10      36. The rotary module of claim 29, wherein the function compartments are disposed around the respective valve surfaces for conveying gas to and from the flow paths in a common predetermined sequence for each flow path, the sequence comprising the steps of
- 15      (1) supplying the gas mixture at the upper pressure from a first function compartment as a feed compartment to the flow path first end while removing gas enriched in a less readily adsorbed component as a light product gas at substantially the upper pressure from the flow path second end to a second function compartment as a light product compartment, (2) releasing gas enriched in a less readily adsorbed component from the second end as light reflux gas so as to reduce the pressure in the flow path to an intermediate pressure level, (3)
- 20      releasing gas enriched in a more readily adsorbed component from the first end as countercurrent blowdown gas so as to reduce the pressure in the flow path from an intermediate pressure level, (4)
- 25      removing gas enriched in a more readily adsorbed component as a heavy product gas at the lower pressure from the first end to a first function compartment as a heavy product compartment, and (5)
- 30      supplying light reflux gas at a pressure intermediate the upper and lower pressure to a light
- 35

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reflux return compartment and thence to the second end.

- 5        37. The rotary module of claim 29, with the sequence also including after step (5) a step (6) supplying the gas mixture at an intermediate pressure less than the upper pressure to a feed pressurization compartment and thence to the first end.
- 10      38. The rotary module of claim 29, wherein each function compartment is shaped to provide uniform gas flow through the corresponding sector of the first or second rotary valve face.
- 15      39. The rotary module of claim 29, wherein each of the function compartments simultaneously communicates with apertures to at least two angularly spaced adsorber elements so as to provide substantially uniform gas flow at substantially steady pressure through each of the function compartments.
- 20      40. The rotary module of claim 29, wherein dead volume associated with the first and second apertures is substantially zero.
- 25      41. The rotary module of claim 29 wherein flow channels in a flow path are provided as a plurality of substantially identical parallel passages through the adsorbent material.
- 30      42. The rotary module of claim 41, wherein the adsorbent material is supported in thin sheets, the sheets are laminated with spacers therebetween, and the flow channels are established by the spacers between adjacent pairs of the sheets.
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43. The rotary module of claim 42 with fluid sealing means cooperating with the stator to limit fluid leakage between function compartments in each of the first and second rotary valve sealing faces, and to substantially prevent fluid leakage from or into each of the first and second rotary valve faces.
44. The rotary module of claim 43, with the rotor having a first rotor face for engaging the fluid sealing means in the first rotary valve surface and a second rotor face for engaging the fluid sealing means in the second rotary valve surface, the first rotor face being penetrated by the first apertures and the second rotor face being penetrated by the second apertures, for cyclically exposing each adsorber element to a plurality of discrete pressure levels between the upper and lower pressures.
45. The rotor module of claim 29, wherein an adsorber element in each flow path is formed from a plurality of adsorbent sheets, each said sheet including a reinforcement material, an adsorbent material deposited therein, a binder for securing the adsorbent material, and a spacer provided between each adjacent pair of adsorbent sheets for providing the flow channel therebetween.
46. The rotor module of claim 45, wherein the reinforcement material is selected from a mineral or glass fiber matrix such as a woven or non-woven glass fiber scrim, a metal wire matrix such as a wire mesh screen, or a metal foil such as an anodized aluminum foil.
47. The rotor module of claim 29, wherein the adsorbent material comprises a zeolite.

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48. The rotor module of claim 45, wherein the reaction space is a zone of the adsorber element with a heterogeneous catalyst contacting the flow channels therein.
- 5
49. The rotary module of claim 29, in which the composition of the adsorbent material is selected to be different in each of multiple zones along the flow path between the first and second ends.
- 10
50. The rotary module of claim 49, in which the adsorbent material in at least one of the zones is active as a heterogeneous catalyst.
- 15
51. The rotor module of claim 45, wherein the adsorber elements include a pair of opposite ends, and each said aperture is disposed immediately adjacent to a respective one of the opposite ends.
- 20
52. The rotary module of claim 29, with the rotor having an annular volume containing the adsorber elements, with the flow direction being axial with respect to the axis of rotation, and with the first rotor face being a circular annular end surface of the rotor and the second rotor face being a circular annular end surface of the rotor, the first and second rotor faces being substantially normal to the axis of rotation.
- 25
53. The rotary module of claim 29, with the rotor having an annular volume containing the adsorber elements, with the flow direction being substantially radial with respect to the axis of rotation, and with the first rotor face being an external cylindrical surface of the rotor and the second rotor face being an internal cylindrical surface of the rotor.
- 30
- 35

FIG. 1

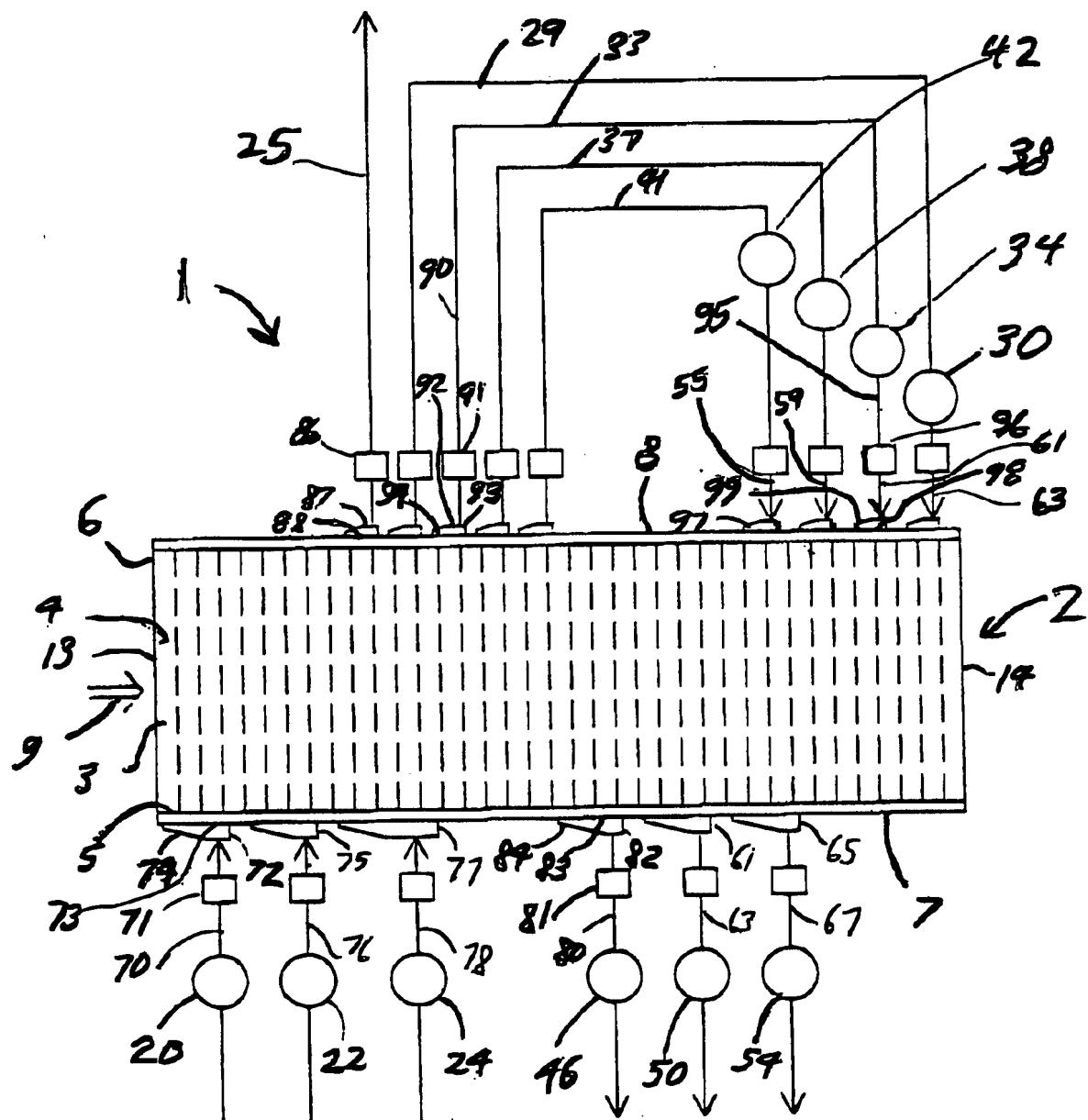


FIG. 2

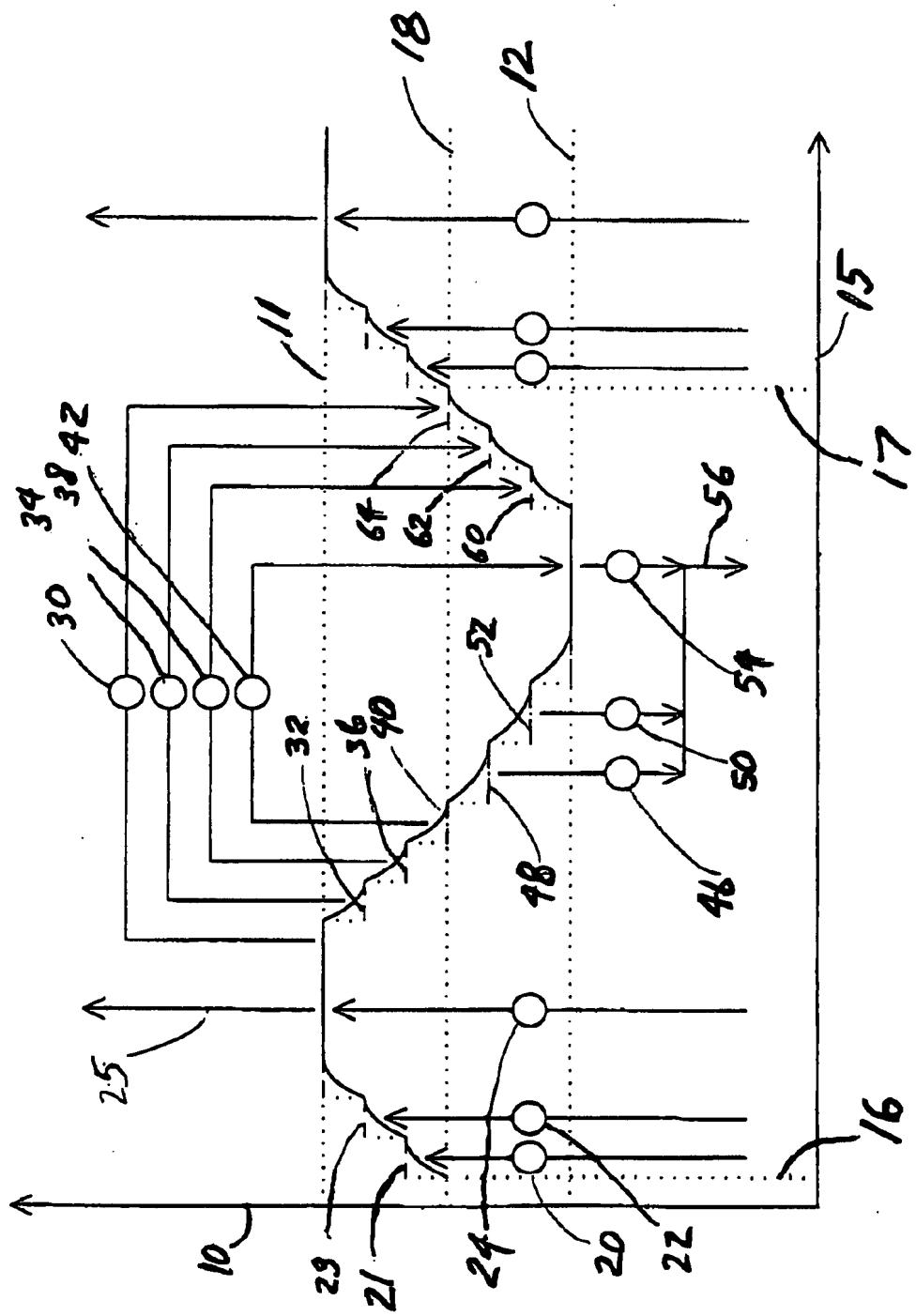


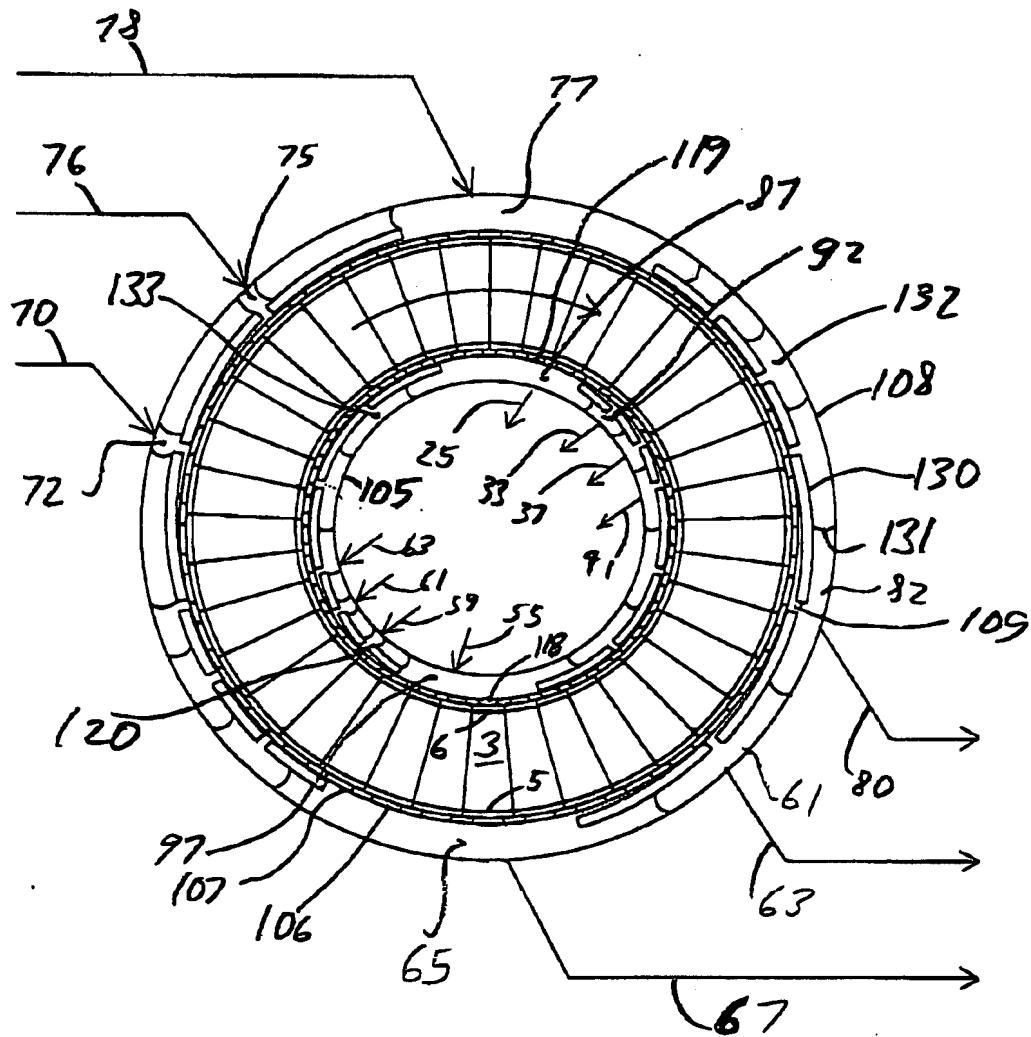
FIG. 3

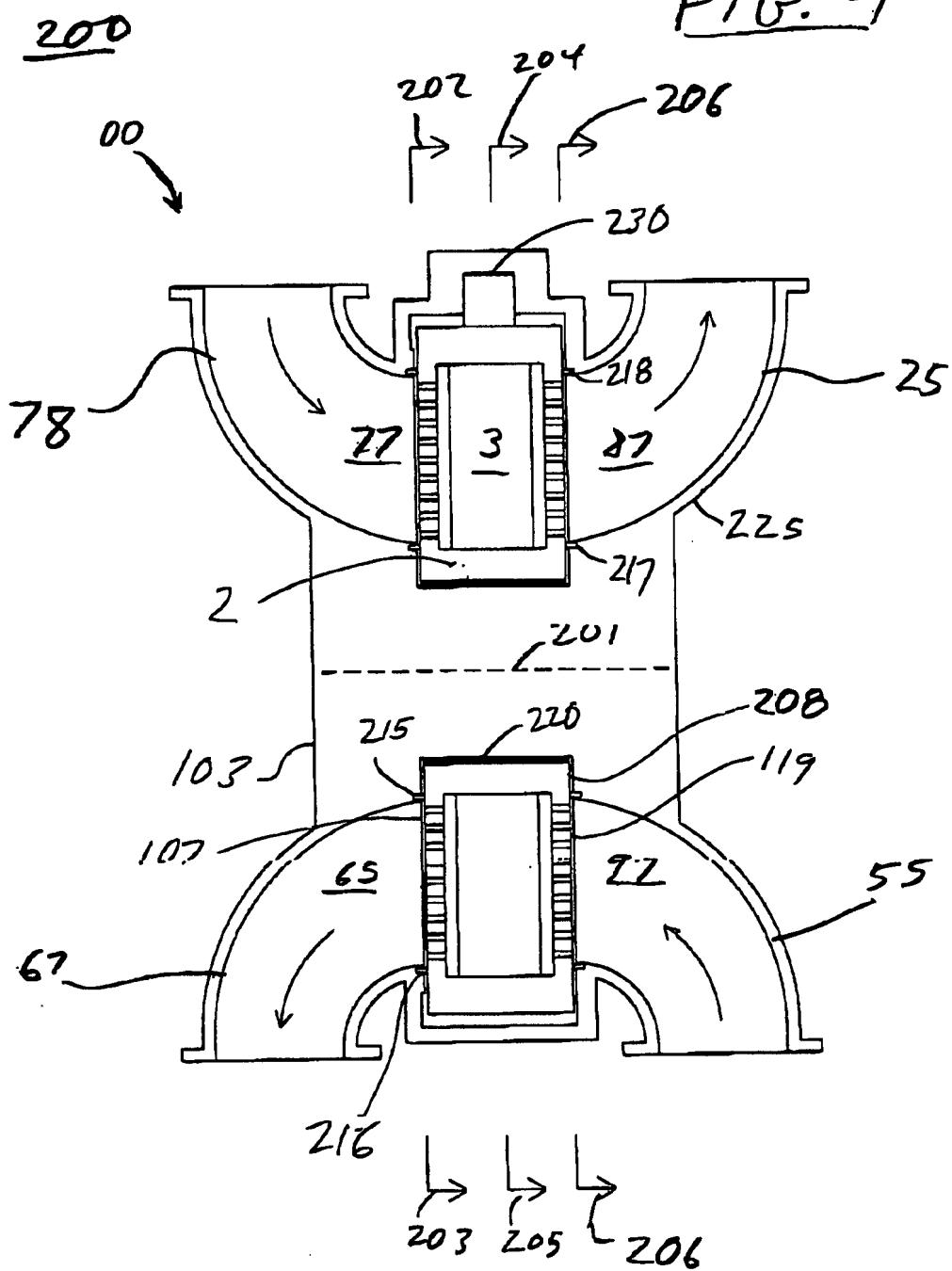
FIG. 4

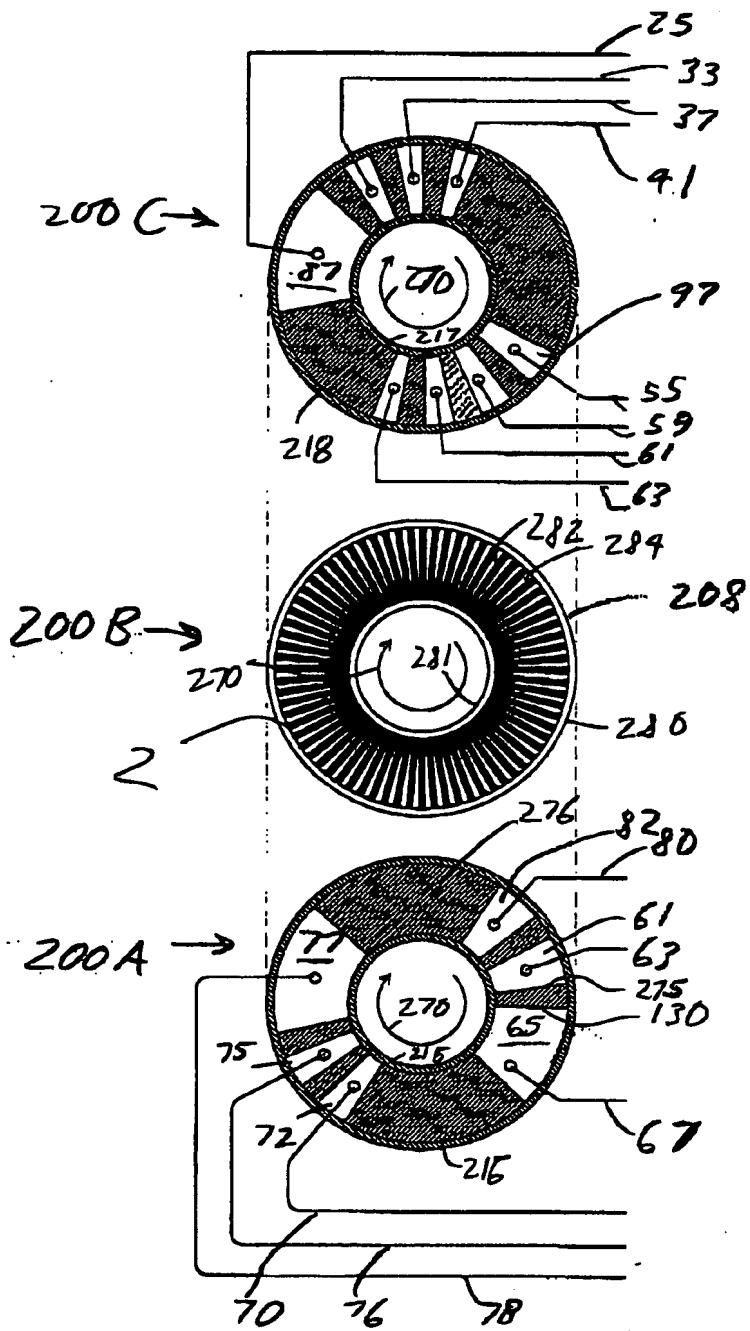
FIG. 5

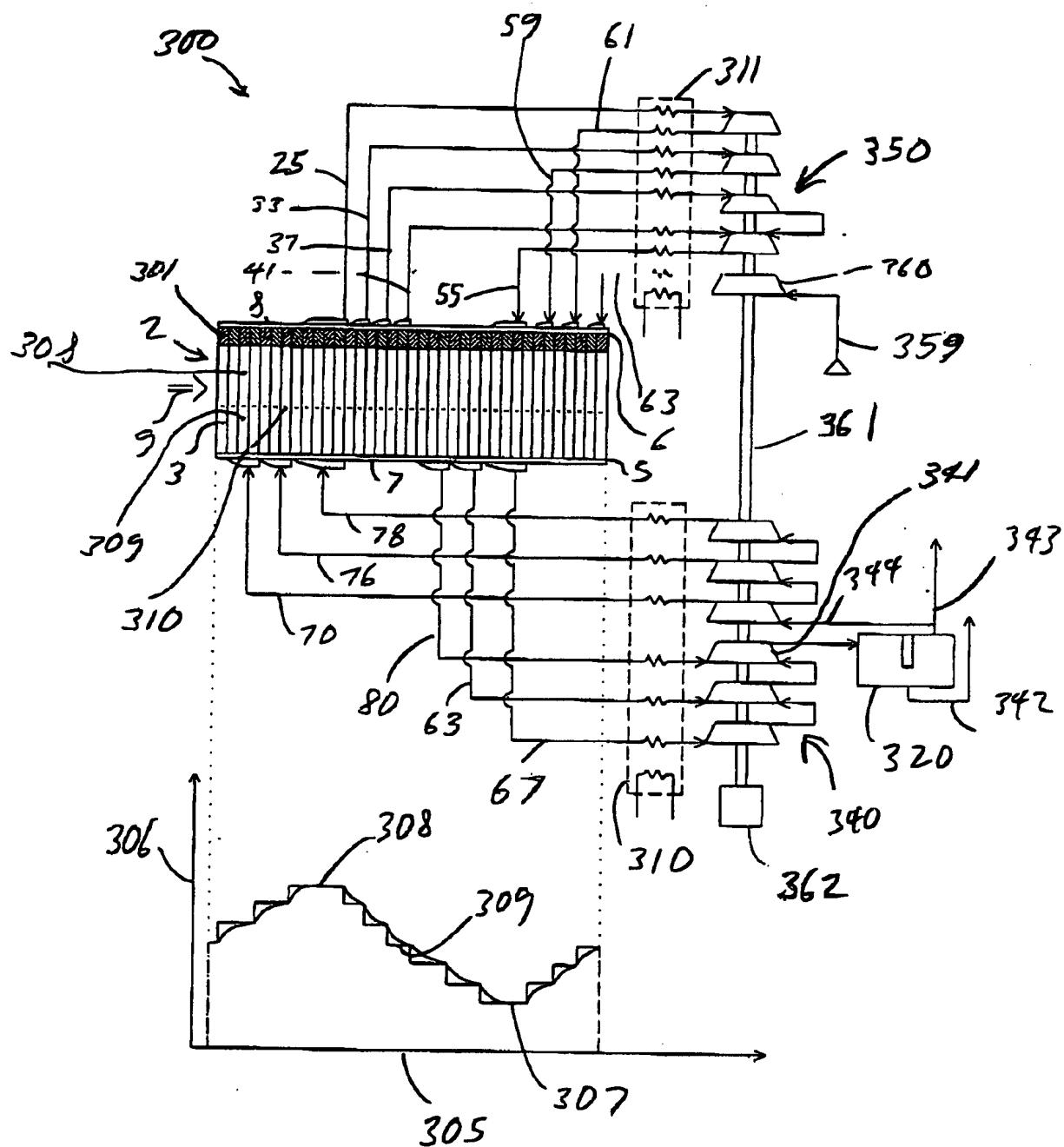
FIG. 6

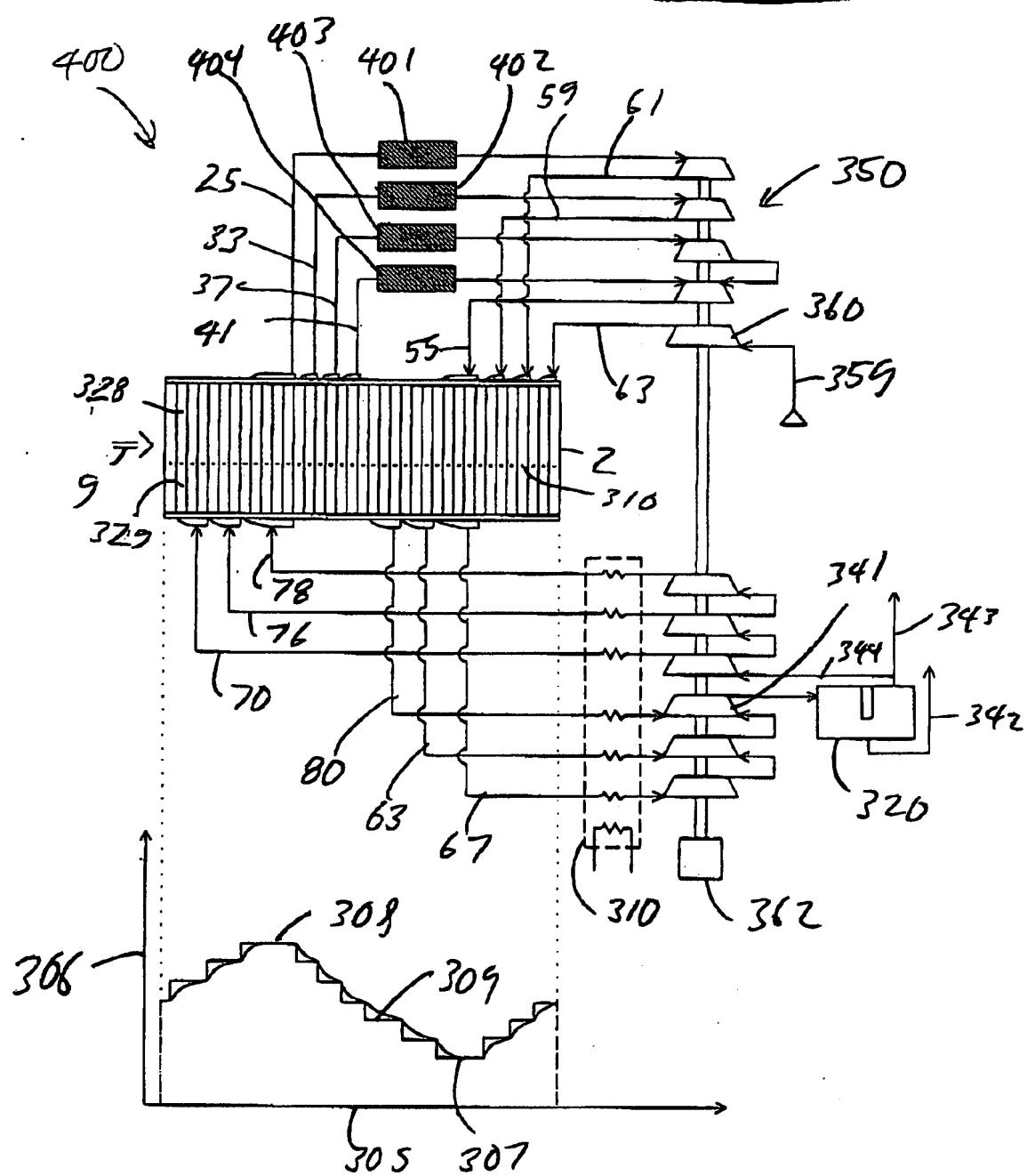
FIG. 7

FIG-8